# Annotated Bibliography

## 13.02 Slope Limitations for Tractor Operation

Skid trail erosion occurred more heavily in ravines than on hillsides. Basalt skid trails showed less intensive erosion than granite skid trails. At 1 percent, the difference was insignificant, most likely due to soil characteristics.
*Kidd, 1963*

Skid trail plots made by a D6 cat were measured for one-year erosion rates. Values were measured in tons/acre and area-inches. Slopes refer to skid trail gradients.

| | | | |
|---|---|---|---|
| 15% slope | Ash with litter | 0.28 | 0.003 |
| 45% slope | Ash with litter | 0.30 | 0.004 |
| 15% slope | Ash without litter | 1.00 | 0.012 |
| 45% slope | Ash without litter | 1.86 | 0.022 |
| 15% slope | Exposed subsoil | 20.46 | 0.164 |
| 40% slope | Exposed subsoil | 72.6 | 0.583 |
| 50% slope | Subsoil covered with slash | 1.08 | 0.013 |

Slope gradients from 15 to 40 or 45 percent increased erosion. Erosion rates increased by factors of 1.2, 1.7 and 3.7 at increased gradients for ash with litter, ash without litter and exposed subsoil plots. "However, the effect of the soils, litter and slash variables were much greater than those of slope. Both of the exposed subsoil plots had high erosion rates, even on the gentler slopes; whereas all of the volcanic ash topsoil plots had low erosion rates, even on steeper slopes."
*McGreer, 1981*

Studies performed at variable slopes, many exceeding 45 percent, estimated that for the first five years after cat logging, annual erosion on skid trails was 0.1 foot.
*Arnold and Lungreen, 1968*

At slopes of 67 percent, jammer and skyline skidding increased sediment deposits an average of 0.04-tons/square mile/day in ephemeral drainages. Control watersheds showed 0.6 times less sediment. Sediment increases up to 750 times greater were found on roads supporting jammer logging.
*Megahan and Kidd, 1972b*

On slopes greater than 50 percent, tractor and jammer skidding prevented the proper role of road drainage systems and inflicted disturbance and damage to road prism components. This disturbance has created serious sedimentation problems.
*Hartsog and Gonsior, 1973*

In southeastern British Columbia, steep slope sites caused soil disturbance of 15 and 45 percent, ground skidding and grapple yarding was 22 and 30 percent, and head-lead yarding 11 and 16 percent.
*Krag et al, 1986; Smith and Wass, 1976; Thompson, 1988*

## 13.04 Re-vegetation of Surface Disturbed Areas

A study was conducted to evaluate plant density, percent ground cover, and survival associated with the various scarification treatments, mulch/fertilizer applications and species selections for seeding roadbeds. After log hauling in the fall of 1955, two roads were used to study treatments applied to 128 plots. One road was mainly a north aspect, and the other mostly south. Information was collected in July of 1957 and July of 1958. For the duration of the study, probability for grass establishment was high due to above normal precipitation. If there had been drought, results probably would have varied. Reseeding was successful. Treatments showed an average of 9.4 and 10.7 plants/foot$^2$ and the plants/foot$^2$ ranged from 1 to 33, respectively, in both years. The range for counts in the reseeding treatment was 6.9 to 11.1plants/ foot$^2$. The range for ground cover was from 5.8 to 13.0 percent. The growing conditions seemed to be best suited for manchar smooth bromegrass, intermediate wheatgrass and standard crested wheatgrass.
*Kidd and Haupt, 1968*

Fill roads were constructed in 1978 and 1979. From spring 1980 to spring 1981, surveys were conducted on rills, gullies and slumps. All fillslopes had been fertilized, seeded and hydro-mulched. Sediment flows influenced by culverts were excluded. Average sediment transport downslope was 8.4 feet below rills, varying from 0 to 53 feet. Fillslope length, vertical height, sediment volume, bulk density and obstruction index were all statistically significant for transport distance.
*Carlton, King and Tennyson, 1982*

Two roads were chosen for this study, each a mile long, one with slopes facing south, and the other north. Earthen drains were constructed on each road at intervals ranging from 50 to 100 feet. A total of 128 plots were taken, 64 per road, with each interval between cross drains a study plot. Different scarification treatments were applied to each study plot.

1) On the first, no roadbed preparation was done before or after broadcast seeding – this was the control plot;
2) The second plot was scarified 3 inches deep with a spike tooth harrow after seeding;
3) The third was scarified 12 inches deep with a six-tooth ripper mounted under a road patrol after seeding; and
4) The fourth was deep scarified 12 inches, then seeded.

More treatments were superimposed on the scarified plots after seeding, namely:

1) On the first, fertilizer equivalent to 40 pounds of nitrogen plus 40 pounds of phosphorous per acre was broadcast with hand spreaders;
2) On the second plot, a layer of wood chips about 1 inch thick was spread over the plot manually with pitchforks – the chips were produced by feeding green ash into a tractor-mounted chipper; and
3) The third had a combination of fertilizer and wood chips.
4) On the fourth plot, only the scarification treatment was applied.

Some extraneous circumstances affected the outcome of the study. In the fall, some of the seed broadcasters were lost due to late winter germination. In some plots, small animals were seen collecting seeds during seeding, resulting in a non-uniform distribution. These factors could cause differences in results not attributable to treatment methods. Another variable could have been the time between seeding and germination, when two periods of heavy overland flow occurred.

The plots were studied for two years, and produced from 1 to 33 plant species per $foot^2$. After the first year, average plant density for all treatments was 9.4 per $foot^2$. The second year, average plant density for all treatments was 10.7 per $foot^2$ if the 21 grazed plots were excluded, and 8.5 per $foot^2$ if they were included.

Effects of Scarification Treatments

| | Plants per square foot | | Percent ground cover | |
|---|---|---|---|---|
| Treatment | 1957 | 1958 | 1957 | 1958 |
| Broadcast seed (control) | 9.4 | 10.7 | 8.2 | 12.5 |
| Seed, harrow | 9.3 | 12.2 | 5.4 | 13.6 |
| Seed, deep scarify | 5.4** | 7.1** | 8.6 | 11.9 |
| Deep scarify, seed | 13.4* | 12.5* | 8.0 | 11.2 |

*Comparison with control significant at 7 percent level
**Comparison with control significant at 5 percent level

*Kidd and Haupt, 1968*

## 14.02 Timber Harvest Unit Design

Sixteen compartments were studied to test the amount of soil area bared by different harvest types. Stem selection cuts were done in 8 compartments, and the other 8 were group selection cuts. As the cutting intensity increased in the stem-selection areas from 1500 to 6500 trees per square mile, the amount of soil bared increased from 29 to 114 acres per square mile. For group-selection areas, the same increase in cutting intensity increased the amount of bared soil from 29 to just 84 acres per square mile.

The trees were more dispersed in the stem-selection compartments, so skid trails were not reused as much, and haul roads accounted for more bared soil. Different tractor sizes resulted in no significant difference in aerial disturbance in the group-selection areas. Results showed that group-selection cutting resulted in less soil disturbance than single tree selection.
*Haupt, 1960*

In this study, long-term changes were quantified in storm hydrograph behavior associated with clear-cuts and road construction, and alternate hydrologic mechanisms were examined to explain stream hydrograph changes in western Oregon.

Three small-basin watersheds were used – they are tributaries of Lookout Creek in the H.J. Andrews Experimental Forest in the western Cascades.

- Watershed 1 was 100 percent clear-cut between 1962 and 1966, but had no roads.
- Watershed 2 was 0 percent clear-cut, also with no roads.
- Watershed 3 was 25 percent clear-cut in1963, and had 2.7 km of roads, which amounted to about 6 percent of the basin area.

In the first five years following clear-cutting in Watershed 1, for precipitation events of all sizes, average peak discharge increased by more than 50 percent, with storms producing later peaks and earlier rises. By the sixth year, discharge had decreased 10 percent, but was still 40 percent higher than pre-treatment. Peak discharge depended on the size of the event **–** it increased by more than 75 percent for small and 25 percent for large events.

In Watershed 3, five years after clear-cutting, the average peak discharge increased by 50 percent with a 6-hour advance in the beginning mean time of hydrographs. After 25 years, peak discharge decreased, but was still 25 percent higher than pre-treatment. Compared to pre-treatment levels, hydrograph beginning times were still advanced from 7 to 10 hours.

The hydrologic response performs much differently when comparing clear-cutting alone in small basins, to clear-cutting with roads. Peak discharges were increased in all seasons, especially during winter. See tables below for peak-flow response data.

Magnitude and Duration of Peak Flow Response, by size of storm flow event from 1955 to 1988 in 1-$km^2$ Basins in the Western Cascades of Oregon

| | | All events* | | | Small events* | | | Large events* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Years | Treatment | *n* | mean† | index ‡ | *n* | mean† | index‡ | *n* | mean† | index‡ |
| | *100% clear-cutting without roads (Watershed 1)* | | | | | | | | | |
| 1955-1961 | None | 74 | 0.70a | 100 | 29 | 0.67a | 100 | 16 | 0.73a | 100 |
| 1962-1966 | 100% cut | 49 | 0.94b | 134 | 15 | 0.85a | 127 | 8 | 0.97a | 133 |
| 1967-1971 | 0-5 years postcut | 50 | 1.08c | 154 | 18 | 1.18b | 176 | 9 | 0.91a | 125 |
| 1972-1976 | 6-10 years postcut | 58 | 0.95b | 136 | 10 | 0.99ab | 148 | 16 | 0.95a | 130 |
| 1977-1981 | 11-15 years postcut | 54 | 0.97bc | 139 | 21 | 1.02ab | 152 | 12 | 0.88a | 121 |
| 1982-1988 | 16-22 years postcut | 67 | 0.96b | 137 | 19 | 1.03ab | 154 | 14 | 0.88a | 121 |
| | *25% patch cutting with roads (Watershed 3)* | | | | | | | | | |
| 1955-1958 | none | 43 | 0.50a | 100 | 10 | 0.62a | 100 | 15 | 0.44a | 100 |
| 1959-1962 | 6% roads | 50 | 0.60a | 120 | 16 | 0.66a | 107 | 5 | 0.50a | 114 |
| 1963-1968 | 25% cut | 69 | 0.75b | 150 | 20 | 0.93b | 150 | 14 | 0.65b | 148 |
| 1969-1973 | 6-10 years postcut | 53 | 0.70bc | 140 | 17 | 0.86bc | 139 | 13 | 0.64b | 146 |
| 1974-1978 | 11-15 years postcut | 56 | 0.66bc | 132 | 8 | 0.77ab | 124 | 14 | 0.56a | 127 |
| 1979-1983 | 16-20 years postcut | 60 | 0.63c | 126 | 16 | 0.76ac | 123 | 18 | 0.56a | 127 |
| 1984-1988 | 21-25 years postcut | 46 | 0.63c | 126 | 15 | 0.73ac | 118 | 6 | 0.58a | 132 |

Group means in the same column followed by the same letter are not significantly different from each other according to Tukey's highest significant difference multiple comparisons procedure with an overall protection level of $p < 0.05$.

*The size classes are as follows: small events are those with <0.125-year return periods and unit area peak discharges <0.11 $m^3s^{-1}$ $km^{-2}$; small to medium events are those with return periods from 0.125 to 0.2 years (0.11 to 0.21 $m^3s^{-1}$ $km^{-2}$); medium to large events are those with return periods from 0.2 to 0.4 years (0.21 to 0.35 $m^3s^{-1}$ $km^{-2}$); and large events are those with return periods from 0.4 to 100 years (>0.35 $m^3s^{-1}$ $km^{-2}$).

†Mean value for this group of the response variable, defined as the difference in log-transformed matched peak discharges, Watershed 1 minus Watershed 2.

‡The post-treatment mean as a percent of the pretreatment mean in the treated watershed, controlling for changes over time in means in the untreated watershed.

Magnitude and Duration of Peak Flow Response, by season of storm flow event from 1955 to 1988 in 1-km$^2$ Basins in the Western Cascades of Oregon

| Years | Treatment | All events* | | | Fall events* | | | Winter events* | | | Spring events* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *n* | mean† | index‡ | *n* | Mean† | index‡ | *n* | mean† | index‡ | *n* | mean† | index‡ |
| *100% clear-cutting without roads (Watershed 1)* | | | | | | | | | | | | | |
| 1955-1961 | None | 74 | 0.70a | 100 | 27 | 0.73a | 100 | 33 | 0.68a | 100 | 14 | 0.68a | 100 |
| 1962-1966 | 100% cut | 49 | 0.94b | 134 | 18 | 1.06b | 145 | 19 | 0.88b | 129 | 12 | 0.87a | 128 |
| 1967-1971 | 0-5 years postcut | 50 | 1.08c | 154 | 16 | 1.25c | 171 | 28 | 0.95b | 140 | 6 | 1.21b | 178 |
| 1972-1976 | 6-10 years postcut | 58 | 0.95b | 136 | 13 | 0.99b | 136 | 39 | 0.93b | 137 | 6 | 0.96a | 141 |
| 1977-1981 | 11-15 years postcut | 54 | 0.97b | 139 | 17 | 0.94ab | 129 | 28 | 0.99b | 146 | 9 | 0.93a | 137 |
| 1982-1988 | 16-22 years postcut | 67 | 0.96b | 137 | 20 | 0.97b | 133 | 35 | 0.92b | 135 | 12 | 1.06ab | 156 |
| *25% patch cutting with roads (Watershed 3)* | | | | | | | | | | | | | |
| 1955-1958 | None | 43 | 0.50a | 100 | 16 | 0.61a | 100 | 20 | 0.43a | 100 | 7 | 0.46a | 100 |
| 1959-1962 | 6% roads | 50 | 0.60a | 120 | 26 | 0.68a | 111 | 13 | 0.51ab | 119 | 11 | 0.51a | 110 |
| 1963-1968 | 25% cut | 69 | 0.75b | 150 | 24 | 0.87b | 143 | 35 | 0.64b | 149 | 10 | 0.81b | 176 |
| 1969-1973 | 6-10 years postcut | 53 | 0.70bc | 140 | 19 | 0.82bc | 134 | 26 | 0.63b | 147 | 8 | 0.68ab | 148 |
| 1974-1978 | 11-15 years postcut | 56 | 0.66bc | 132 | 16 | 0.72ac | 118 | 32 | 0.62b | 144 | 8 | 0.67ab | 146 |
| 1979-1983 | 16-20 years postcut | 60 | 0.63c | 126 | 19 | 0.75abc | 123 | 33 | 0.58b | 135 | 8 | 0.53ab | 115 |
| 1984-1988 | 21-25 years postcut | 46 | 0.63c | 126 | 15 | 0.66a | 108 | 19 | 0.64b | 149 | 12 | 0.60ab | 130 |

Group means in the same column followed by the same letter are not significantly different from each other according to Tukey's highest significant difference multiple comparisons procedure with an overall protection level of $p < 0.05$.
*The seasons are as follows: fall, August through November; winter, December through February; spring, March through June.
†Mean value for this group of the response variable, defined as the difference in log-transformed matched peak discharges, Watershed 1 minus Watershed 2.
‡The post-treatment mean as a percent of the pretreatment mean in the treated watershed, controlling for changes over time in means in the untreated watershed.

*Jones and Grant, 1996*

According to the Interim Harvesting Guidelines of British Columbia, where the soils are low to moderately sensitive, soil disturbance should be no more than 19 percent. Where soils are highly sensitive, soil disturbance should be no more than 9 percent. These limits have generally been exceeded on steeps slopes in interior B.C. Studies found that the 19 percent limit was usually achieved only during conventional winter operations *[Smith and Wass, 1976; McCleod and Hoffman, 1988]*. No highly sensitive sites achieved the 9 percent limit. Even where the 19 percent limit was achieved, disturbance levels for skid trails exceeded the 15 percent subtotal by type. Other studies found that soil disturbance targets for moderate sites can be met through the use of small crawler tractors for skidding, although skid road soil disturbance may exceed the limit *[Krag and Webb 1987; McMorland 1980 and Smith 1988]*.
*Krag, Mansell and Watt, 1991*

## 14.05 Protection of Unstable Areas

Studies performed on slope steepness, found that steepness was a large factor in road-related failures. The recommendation is that "no un-retained slopes should be allowed in excess of 35 degrees or 70 percent on road fills."
*Gonsier and Gardner, 1971*

## 14.06 Streamside Management Zone Rules, Riparian Area Designation

Buffer strips of undisturbed vegetation 100- and 200-feet-wide were set up in paired sampling stations. Parameters were measured at stations upstream and downstream of a clearcut in areas that were clear-cut and slash burned. For stations with buffer strips, the parameters with significant increases were electrical conductivity, bicarbonate, sulfate calcium and magnesium. Sampling stations with no buffer strips showed increases in all of the above parameters, plus increases in pH, turbidity, suspended solids and potassium.
*Snyder, 1973*

Damming from slash and debris resulted in stream blockages caused by skidding logs across

stream bottoms.  Turbidities measured at 7 ppm were increased to 100 ppm when logs were skidded across the stream.  A control watershed was measured at 6 ppm.
*Bachmann, 1958*

A paired watershed study was conducted.  The treated area was helicopter logged and slash was burned according to prescription.  Averaging 25 meters wide, buffer strips of undisturbed vegetation "except for removal of trees that were expected to die prior to the next timber harvest," were left between perennial streams and cutting units.  During a 10-year period following treatment, total sediment yield increased 94 percent at the watershed mouth. Accelerated surface erosion accounted for about 95 percent of the increased surface erosion, "resulting primarily from broadcast burning."  Mass erosion accounted for about 5 percent of cutting units.
*Megahan, 1987; Megahan draft*

### 14.07 Determining Tractor-Loggable Ground
Tractor logging generally produced disturbances of from 20 to 35 percent of a harvested area. Jammer, skyline-crane cable systems, and high lead disturbed about 11 to 16 percent of the harvested area.
*Dyrness, 1965; Fowells and Shubert, 1951; Garrison and Rummell, 1951; Haupt, 1960; Steinbrenner and Gessel, 1955; Wouldridge, 1960.*

Studies found that skyline systems produced soil disturbance of from 5 to 14 percent in harvested areas *[Amaranthus and McNabb, 1983; Dyrness, 1965; Ruth, 1967],* harvesting with a balloon caused 6 percent *[Dyrness, 1972]* and helicopter logging produced 5 percent disturbance.
*Clayton 1981.*

### 14.08 Tractor Skidding Design
A trail system limited to no more than 10 percent of the total harvest area was studied for log skidding efficiency.  An area of 12.4 acres was logged with designated skid trails.  Skid trails were flagged in parallel routes, with spacing of 100, 150 and 250 feet.  For each spacing, two trails 600 feet long were established.  On an adjacent plot, a 9.9-acre tract was thinned conventionally, and the logger chose the route and design of skid trails.  A rubber-tired skidder was used to skid and deck the logs.

In the unit that was conventionally thinned, 20 percent of the ground surface consisted of skid trails.  In the area where skid trails were 100 feet apart, skid trails comprised 11 percent of the area, 7 percent where trails were 150 feet apart, and only 4 percent where trails were 250 feet apart.
*Froehlich, Aulerich and Curtis*

Productivity with the Conventional and Designated Trail Systems

| Variable | Designated trails | Conventional trails |
|---|---|---|
| Winch cycle (minutes)[1] | 3.48 | 3.72 |
| Winch cycles/turn | 1.78 | 1.50 |
| Winch time (minutes/turn) | 6.19 | 5.57 |
| Skidding time (minutes)[1] | 5.83 | 7.02 |
| Total turn time (minutes)[2] | 12.02 | 12.59 |
| Logs/turn | 4.08 | 3.96 |
| Logs/hour | 20 | 19 |

[1]Average values in table 1 applied to equations in table 2.
[2]Winch time plus skidding time.

On ground-skidded areas, skid trails account for most of the soil disturbance. This explains why higher levels of disturbance are associated with ground skidding compared to cable-yarding *[Krag, 1984]*. On three sites harvested with small tractors, soil disturbance from skid trails ranged from 12.3 to 14.2 percent, compared to 28 percent on areas harvested with big tractors *[McMorland, 1980].* Researchers found that locating skid trails before harvest greatly reduced disturbance and restricted skidders to designated trails.
*Froehlich et al, 1981; Olsen and Seifert, 1984*

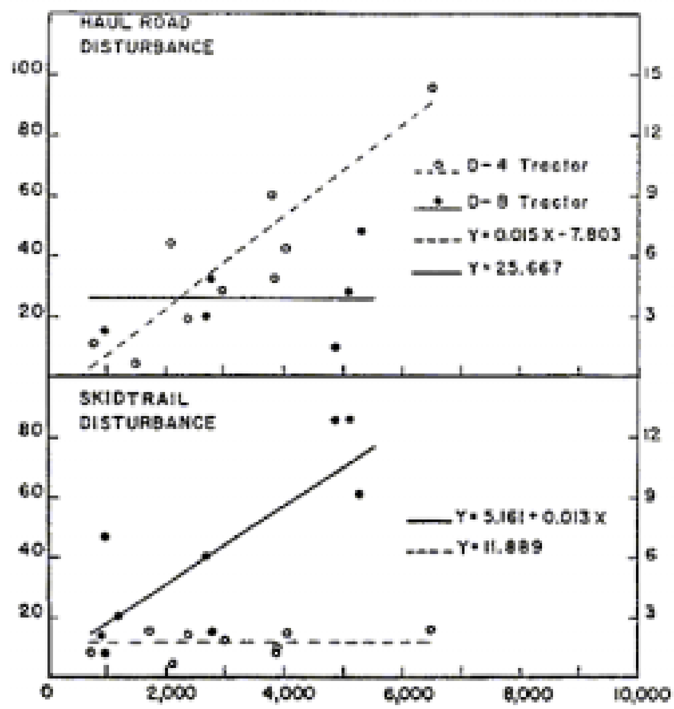
## 14.15 Erosion Control on Skid Trails

On skid trails at a 15 percent grade with volcanic ash topsoil intact, first-year erosion was reduced by 72 percent by leaving a remnant layer of litter. On a 45 percent grade, erosion was reduced by 84 percent. Placing slash on skid trails reduced first-year erosion rates by blading away volcanic ash topsoil and leaving alluvial subsoil exposed. Erosion on skid trails of 50 percent slope treated with slash, was 98.5 percent less than on skid trails of 40 percent slope without slash, and 94 percent less than 15 percent slopes without slash. "Skid trails with exposed alluvial subsoil had much higher erosion rates and slower recovery than skid trails on volcanic ash topsoil."
*McGreer, 1981*

A study was conducted using "good logging practices" intended to minimize erosion associated with logging and logging construction. These practices included reusing skid trails, no skidding down channels, limited skidding across channels, seeding skid trails, cross-ditching roads, and seeding and harrowing roads. During the first four years, rill erosion on skid trails was contained downslope in the next rill erosion structure. Rehabilitation structures caused skid trails to stabilize within three years. "Most sediment en route to and in channels was from haul roads; roadways were re-vegetated and stabilized within four years."
*Haupt and Kidd, 1965; follow-up to Haupt, 1960*

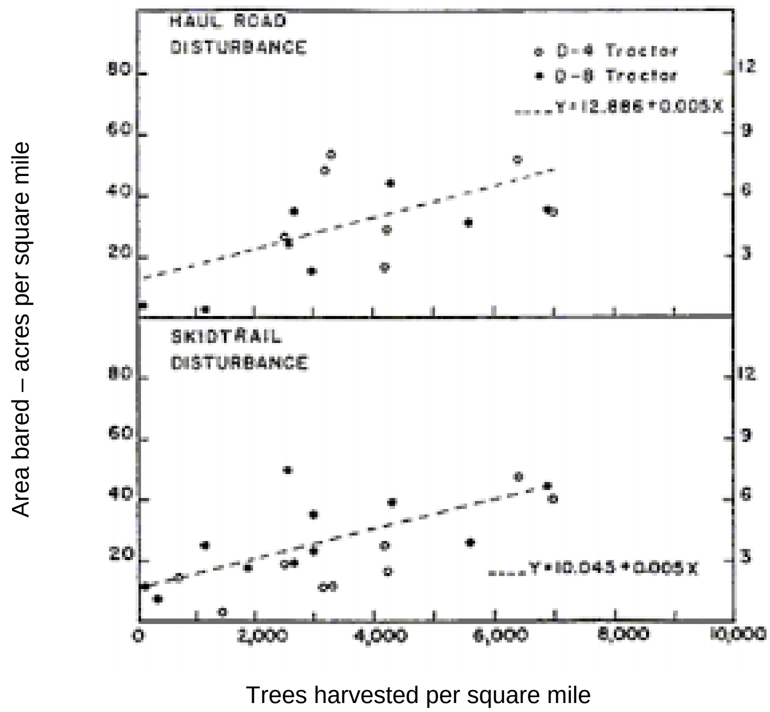
Research was performed on four treatments to determine the type and aerial extent of soil disturbance. The four methods were reserve volumes, the size of tractor, initial stand volumes, and silvicultural systems. Bared areas and skid trails averaged 33 acres/mile for small D4 tractors; bared area averages were 34 and 19 acres/mile for large D8 tractors. Intensified harvesting for stem selection with smaller tractors increased road area, while skid trails remained constant. With large tractors, skid trails increased while road area remained constant. Regression analysis showed that for any given level of harvest, under a stem selection system, total bared area would be greater for large tractors than for small tractors. "Results of the present study indicate rather conclusively that essential haul disturbance is associated with the use of small tractors in stem selection cutting."
*Haupt, 1960*

Area bared – acres per square mile




Trees harvested per square mile

Effects of large and small logging tractors on the relation of soil disturbance from haul roads and skid trails to the intensity of harvest cutting ponderosa pine by stem selection.




Combined effects of large and small logging tractors on the relation of soil bared from haul roads and skid trails to the intensity of harvest cutting ponderosa pine by group selection.

### 15.02 General Guidelines for the Location and Design of Roads and Trails

Sediment flow distance was tested with seven variables, including road width, road cut height and embankment slope length. Studies were done below logging roads that had been "put to bed." The "slope obstruction index," cross-ditch interval squared, embankment slope length, product of the cross-ditch interval and road gradient, had the highest relation. "In the regression equation, an increase of 1 foot of embankment slope length increases sediment flow distance by about 3.5 feet." The range of embankment slope lengths used to develop the equation was from 1 to 32 feet.
*Haupt, 1959 (a,b)*

Fifty percent is the recommended building angle for fills. Fills that are less than 100 feet long, will have limited construction on slopes of 45 percent or less. For fillslopes less than 50 feet long, construction should be limited on slopes of 30 percent or less.
*Jensen and Cole, 1965*

Road prism component values for river terraces and strongly glaciated granitic lands are 0.1-inch surface erosion/year. Values for tread/ditch and fill are .1 inch, and for peri-glaciated granitic lands, the cut value is .2 inches. The cut value for decomposed granitic lands and tread/ditch is 1.0 inch; the fill value is .5 inch.
*Jensen and Finn, 1966*

An evaluation was conducted during construction and for the early period of use on a road that was designed to minimize watershed impacts. Fills were constructed at a repose angle of from 70 to 80 percent, but had been designed for 67 percent, eroded during high intensity rains and showed signs of sloughing and settling cracks. The recommendation was to "minimize heights of cuts and fills and width of tread, sacrificing road alignment as necessary."
*Hartsog and Gonsior, 1973*

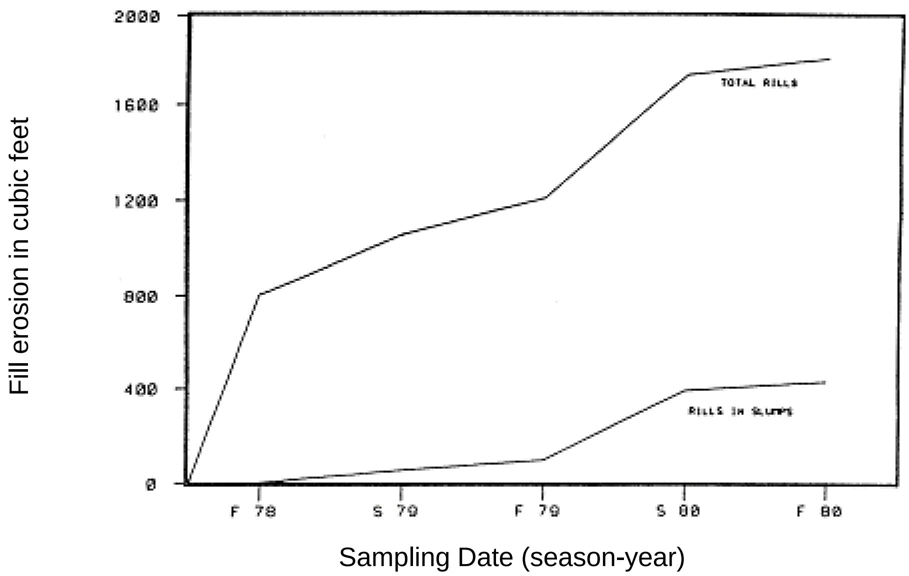
For two years after road construction, sediment flows from gully- and rill-erosion of road fills were measured to see how far they traveled. Maximum flow was 150 feet. Slumps showed a higher average travel-distance than flows originating on non-slumped fills. Flows originating from slumps traveled an average 41.4 feet, compared to 24.2 feet for non-slumped flows.

After the first year, no sediment was transported past the fills with slash-filter windrows. After the second year, sediment flowed an average of 3.8 feet below windrows. For flows not associated with windrows or relief culverts, 73 percent was deposited within 50 feet of the road fill. The most important predictor for travel distance was gully volume. Whether or not run-off occurred from the road surface was also important. During the second year, sideslope grade and fillslope height also were significant.
*Tennyson, King and Prud'homme, 1981*

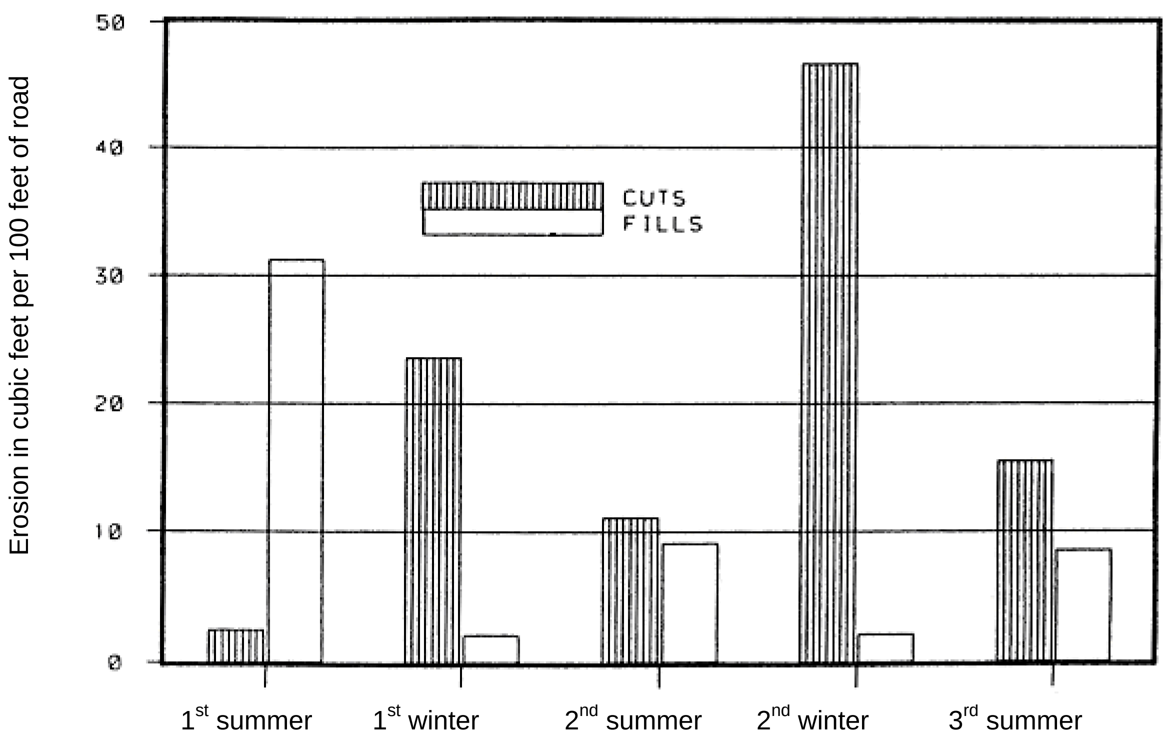
Mean travel distance of fill material below rills and gullies for different fill conditions for Road 9704, stations 0+00 to 79+05

| Sampling Date | Fill Condition Code [1]: 3 | 5 | 6 | 7 | 8 | 9 | 10 | total |
|---|---|---|---|---|---|---|---|---|
| | Number of rills/mean travel distance in feet | | | | | | | |
| Fall 1978 | 2 73.5 | | | 16 0.0 | 7 59.1 | 7 62.9 | 208 8.1 | 240 11.2 |
| Spring 1979 | 1 122.0 | | 8 15.4 | 35 0.0 | 10 65.4 | 4 108.3 | 182 12.2 | 240 14.9 |
| Fall 1979 | 1 122.0 | 2 - | 15 38.0 | 37 2.5 | 12 69.5 | 6 83.3 | 168 14.6 | 241 18.9 |
| Spring 1980 | 1 122.0 | | 29 35.6 | 45 3.8 | 14 64.1 | 5 67.6 | 154 23.2 | 248 24.7 |
| Fall 1980 | 1 122.0 | | 34 41.4 | 45 3.8 | 15 59.8 | 5 67.6 | 148 24.2 | 248 26.3 |

3 = gully below culvert outfall
5 = no distance data recorded
6 = rill or gully in slumped material
7 = rill or gully above filter windrow
8 = combines with culvert outfall
9 = reaches a live stream
10 = all other situations




Total rill erosion and rill erosion in slumped material over time for Road 9704, stations 0+00 to 79+05




Average cut and fill slope erosion for the summer and winter periods

In 1969, a large spreading population of Douglas-fir beetle was found in the South Fork drainage. The China Glenn road was built to salvage the beetle-killed trees and protect the residual stand. The desired road would minimize impacts to the land and meet the needs of the loggers. It took two years to build. During the first year, 2.25 miles were completed. Design guidelines included a 90-foot radius of curvature, maximum grade of 10 percent, a minimum of 1½:1 for fill-slopes and 1:1 for cut-slopes. Most cut-slopes in the first section of road were built at 1½:1 and did not show any signs of failure.

In the section of road built the second year (1.23 mi.), cut-slopes were built near vertical (1:1) and not more than 6 feet high. In the second section, both cut and fill slope heights were less because of the vertical cuts and the more rolling grades of contours. On cuts greater than 1:1, sloughing potential and structural stability depended on how well drained the soils were.
*R.B. Gardner, William S. Hartsog and Kelly B. Dye*

In 1985, Kennedy studied the effectiveness of erosion mitigation measures on 75 to 100 miles of road. Mitigation measures were for cross-drain spacing or crushed aggregate ditch-line armoring. On many of the new roads observed, the ditch-line armoring had failed. On all the newly constructed roads with crushed aggregate armoring, all showed armoring failure. Where the ditch lines were from 7 to 18 percent, was where the failures took place, with more failures where grades exceeded 10 percent. Vegetation was not disturbed even though rock washed from the ditch. In-slopes of up to 12 percent and roads as wide as 40 feet, as well as ditches from 1 to 2 feet or more deep, seemed to contribute most to failures. Failures occurred where cross-drains were spaced as much as twice as far apart as guidelines recommended.

On older roads with ditches and no armoring, the main factors in ditch-line erosion were ditch grade, road surface in-slope and roughness, ditch geometry, cross-drain spacing, and vegetative cover. Again, ditch-line erosion was most common where grades were excessive and ditches steep, as well as where there was little or no ditch vegetation and where cross-drains were too far apart. Where there was little or no erosion, ditch lines generally were flat bottomed, vegetated, flat (with no in-slope or out-slope), with better cross-drain spacing and rough vegetated surfaces.

Older native-surfaced roads without ditches were also reviewed. The roads were flat, or had out-sloped vegetated surfaces with water bars, and grades of 10 percent or less. The un-maintained, heavily rutted roads where cross-drains were more widely spaced, had the most erosion. Roads with proper cross-drain spacing, good vegetative cover and a rough surface had little or no erosion.
*Kennedy 1985*

## 15.03 Road and Trail Erosion Control Plan

Sedimentation and runoff were measured on a native roadway surface with grades ranging from 6.3 to 13.4 percent. Three study sections were measured during snowmelt and rainstorms. The road had been built in 1980, and was extremely eroded before the first measurements were taken in 1981. It was re-graded before measurements were taken in 1982, and closed for the duration of the study. The study showed the road was less susceptible to erosion in its already eroded condition, than after it was re-graded. The eroded road produced from 75 to 80 percent less sediment after runoff in 1981, than when it was re-graded in 1982.
*Vincent, 1985*

For three years after road construction, treated and untreated cut-slopes ranging in grade from 0.95:1 to 1.8:1 were evaluated for erosion using collection troughs. The treated cutslopes were dry-seeded, hydro-seeded, or hydro-seeded and terraced. The treated slopes showed much lower erosion rates. Untreated slopes yielded 15 times more sediment than dry-treated slopes. Hydro-seed, and hydro-seed plus terrace, had much smaller sample sizes, and the collections may be misleading.
*Department of Geology and Physics, 1984*

For three years following road construction, three treatments were evaluated on cut- and fillslopes. The three treatments were 1) dry seeding, 2) cellulose-fiber hydro-mulch plus seed and fertilizer, and 3) straw-mulch with asphalt tackifier and seed and fertilizer. These treatments were evaluated against an area of no treatment. Straw-mulch with tackifier was the only treatment effective for reducing erosion on cutslopes, from 32 to 47 percent effective. For reducing fillslope erosion, all the treatments were effective. For fills from 20 to 40 feet high, erosion was reduced from 24 to 30 percent. For fills less than 20 feet high, erosion was reduced from 46 to 58 percent.
*King, 1984*

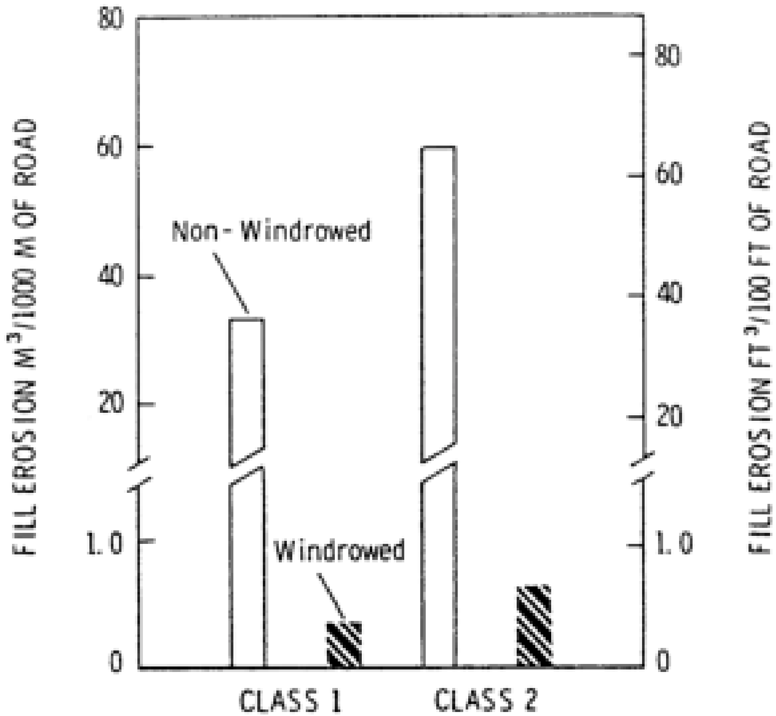
## 15.03 Road and Trail Erosion Control Plan

During road construction, a sediment budget was developed for erosion from roads. "In the fall of the year of the construction, about 85 percent of the eroded material was stored on slopes." Volume and distance the sediment flowed were measured below the road. More sediment flowed farther when associated with berm drains or cross drains, than that originating from fillslopes. The maximum average travel distance was 64 meters; 94 percent moved less than 15 meters. Average travel distance for sediment flowing from drainage structures was 32 meters. The maximum was 118 meters, and 39 percent moved less than 15 meters. The volume of sediment flowing from fills averaged 0.3 meters$^3$, and from drainage structures, 4.7 meters$^3$.
*Megahan, Seyedbagheri, Mosko and Ketcheson, 1986*

Eroded material was collected in troughs below windrowed and non-windrowed fillslopes for three years after road construction. Material was collected for two height classes – Class 1 was from 0 to 10 feet, and Class 2 was from 10 to 20 feet. Fill-slopes were seeded, hydro-mulched, fertilized and had a 1.5:1 slope. Class 2 fillslopes had greater erosion rates for both windrowed and non-windrowed fills.

| | Windrowed | Non-Windrowed |
|---|---|---|
| Class 1 | 0.325 | 35.85 |
| Class 2 | 0.650 | 64.30 |

Measured in feet$^3$ per 100 feet of road length




Fill erosion volumes for windrows and non-windrowed slopes by vertical height during the three years following construction

*Cook and King, 1983*

## 15.06 Mitigation of Surface Erosion and Stabilization of Slopes

The most important factor in reducing surface erosion is percent ground cover. Slope gradient and silt content in the soil surface also can be important. The main objective of this study was to develop effective methods to reduce erosion and sediment production from forest roads. Four components were analyzed, travelway, fillslope, cut-slope, and road ditch.

Simulated rainfall was applied to a 100-foot-long segment of wheel-rutted road in Idaho. The rutted travelway increased sediment production by 2.1 times compared to an un-rutted travelway. Simulated rainfall was applied to an un-graveled road, and to a road with a 4-inch layer of 1½-inch-minus rock. The graveled segment reduced sediment production by 79 percent. Dust oil and bituminous surface treatments were tested using simulated rainfall. Dust oil reduced sediment production by 85.3 percent and bituminous by 96.6 percent.

One of the most cost-effective methods of reducing the sediment that leaves the base of a fillslope is a slash-filter windrow. In a study by *Cook and King, 1983,* the effectiveness of slash-filter windrows was tested for three years. The filter windrow reduced sediment from 75 to 85 percent.

Research performed in northern Idaho on cutslopes using straw-mulch with asphalt tackifier, plus seed and fertilizer, reduced sediment from 32 to 47 percent over a three-year period. Straw mulch and tackifier reduced sediment by about 40 percent, and by 35 percent without the tackifier. On slopes of 1:1 or less, dry seeding reduced sediment by 36 percent.

The most economical and commonly used sediment control treatment for roadside ditches is rock blankets or riprap. A graveled travelway and ditch reduced sediment by 57 percent compared to un-graveled.
*Burroughs, 1988*

Soil ripping is a method of deep plowing used to reduce runoff and erosion by increasing infiltration. In 1995, Aldon found that even three years after treatment, surface runoff was reduced 85 percent and erosion 31 percent. Treatment did not decline until after three to five years, depending on the intensities of summer thunderstorms. A treated plot reduced runoff by two-thirds compared to an untreated plot. The ripping was done with two chisels about 7 feet apart x 4 inches wide x 28 inches deep, opening a furrow at the surface about 15 inches deep.

The study was done on or near the San Luis Watersheds on the Rio Puerto drainage, approximately 58 miles northwest of Albuquerque, New Mexico. The 3 miles of headwaters start on mesas and break off into steep, rocky slopes that ease into rolling hills, which merge with the alluvial bottoms. There are specific perennial grasses on this site including galletta (*Hilaria jamesii),* alkali sacaton (*Sporobolus airoides)* and blue grama (*Bouteloua gracilis).* The site has been grazed from November until April, utilizing 55 percent of the alkali sacation. In 1964, Hickey and Dortignac designed 32 runoff plots to evaluate the effects of precipitation on ripping, and how much ripping decreases runoff and erosion for a three-year period.

On plots that were untreated, runoff averaged about 60 percent of precipitation. At the end of the first year, the treated plots 96 percent effective, 69 percent at the end of the second year, and 85 percent the third year. There was about a 15 percent decline in effectiveness after three years.

Vegetation responded to ripping. Perennial grass cover declined 28 percent after ripping. Before ripping, more than half the forage produced was galetta. Afterwards, more than half was alkali sacaton. Throughout the study, blue gama amounted to about 10 percent of the forage produced. Forage production is shifting back to its original relationship, but will take a couple more years. Ripping was effective only for three to five years, forage production was altered from seven to ten years.
*Aldon, 1976*

### 15.07 Control of Permanent Road Drainage

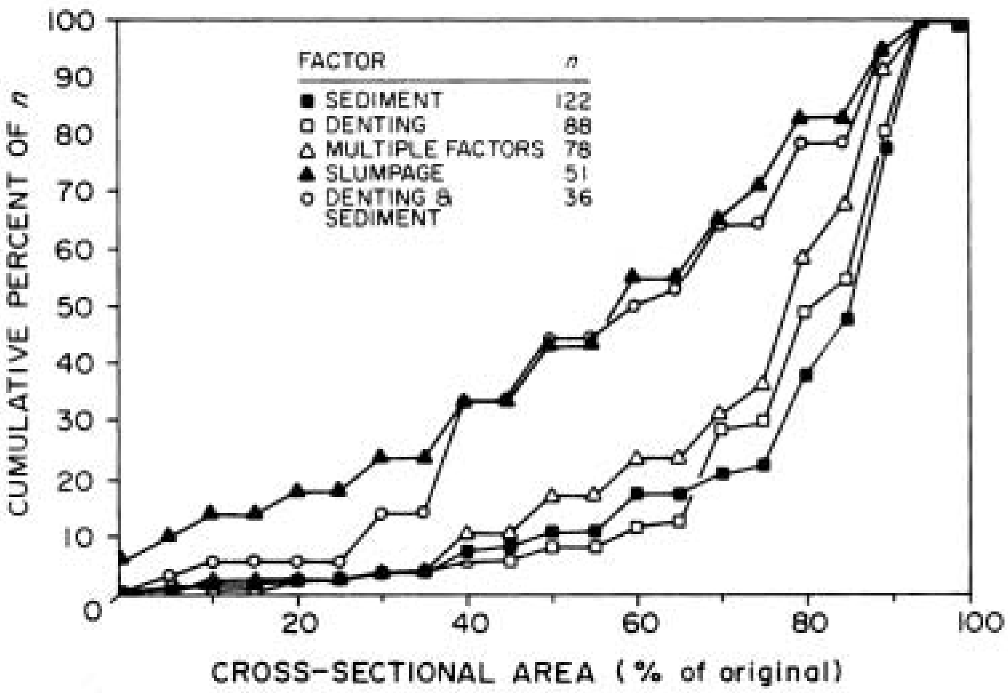
To find specific measurements, including diameter and length, spacing, inlet conditions, skew angle, slope and outlet erosion, 515 ditch-relief culverts were evaluated. Eighty-six percent of the culverts were corrugated steel pipe, with average diameters of 38.1 or 45.7 cm, and 10.7 meters long. Roads were divided into segments and randomly selected. More than 50 percent of the culverts were chosen near ridge tops, on 1- to 1½-lane roads.

Ditch erosion was minimal, except where culvert spacing was exceptionally wide. Ditch-relief culverts had an average cross-sectional area of 81 percent of the original, reducing the average inlet area 74 percent. For 24 percent, sediment deposits were the cause of the reduction, 17 percent were due to physical damage or denting, and 7 percent were a combination. As the cumulative factors increased, the percent area of the original cross-section increased.

Skew angles in this study averaged 15°. More than 90 percent of the culverts had slopes of at least 3 percent, and 40 percent were inclined 2 percent more than the road grade. Average road slope was 7 percent, and average culvert slope was 6 percent.

The largest erosion volumes (841 and 127 $m^3$) were a result of landslides below culvert outlets, comprising 72 percent of total outlet erosion for all ditch-relief culverts. As spacing between culverts increased, erosion volumes increased, with an average of 3.4 $m^3$ where spacing exceeded Arnold's guidelines by 100 percent. Where spacing exceeded these guidelines by less than 10 percent, erosion volumes were only 1.2 $m^3$.

In areas where outlet erosion is a problem, decreasing ditch-relief culvert spacing will decrease outlet erosion.

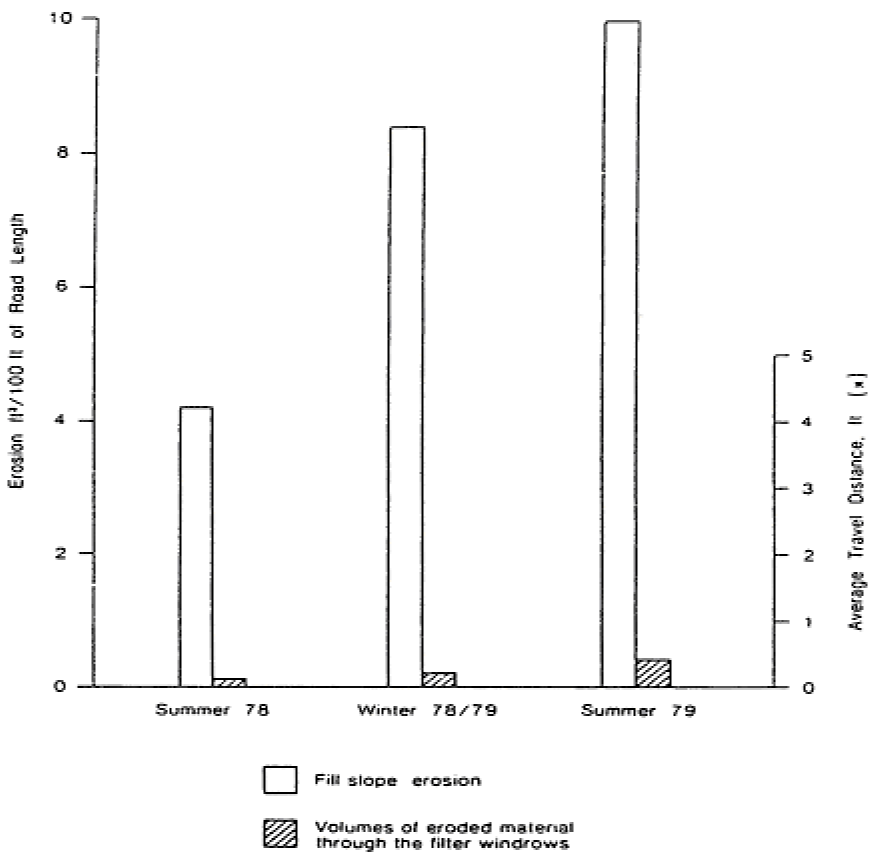



*Piehl and others, 1988*

The effectiveness of erosion control methods, including lopping and scattering slash, slash dams, and log water-bars, were tested on skid trails in granitic and basaltic soils. Effectiveness was rated on a scale of 1.0 to 4.8, where 1.0 was completely effective and 4.8 was least effective. Log water-bars and cross ditches seemed to be more effective than slash dams or lopping and scattering. Log water-bars on granitic basalt rated 1.78 and 1.54, slash dams rated 2.25, and lopping and scattering were 2.93 and 1.60. Slash dams are not desirable on side hills because they are relatively expensive, they cannot divert water, and they quit working and deteriorate in just one to two years. Log water bars are very effective at diverting water on hillside skid trails that are flat, shallow and trough-shaped. Cross ditches are a less expensive alternative to log water-bars. However, cross-ditches are susceptible to sloughing, so every third to fourth bar should be a log water bar for proper water diversion. For gentler slopes, lopping and scattering is recommended because it minimizes the potential for surface flow undercutting.
*Kidd, 1963*

### 15.08 Pioneer Road Construction

How much sediment road construction contributes the first year was measured at stream crossings at three stations. The A stations were above culvert inlets, B stations were below culvert outlets, and the C stations were 100 yards downstream. Pioneering and permanent culvert installation at one crossing caused an estimated 12.3 and 0.2 pounds of excess sediment. At Station C, this was equal to 45 days of average summer low-flow sediment. De-watering or rerouting stream flow around the construction site was the reason culvert installation had such a low value. Forty-six pounds of sediment passed through Station C when another culvert installation was not de-watered – this was equal to 113 days of average summer low-flow sediment. Sediment levels at crossings returned to normal shortly after construction, except during rainstorms, when sediment loads increased 2 to 3 times more than normal at B stations. At one stream crossing, 400 pounds of sediment was measured after the first snowmelt. One year later, sediment loads were only one order of magnitude over normal during summer storms.




Volumes of fill slope erosion and material transported through the filter windrows and the distance of material transported downslope.

*King and Gonsior, 1980*

Three stations were set up to sample sediment production during road construction. Activity was measured at road crossings. Station A was above culvert inlets, Station B was below culvert inlets, and Station C was 100 yards downstream. During pioneering when temporary culverts were placed, sediment loads at C stations varied from 0.00 to 212.59 pounds, with an average of 40.65 pounds. However, this may not represent total sediment because of the fluctuation of flow and transport. For the three crossings tested, the ratio of sediment delivery between stations B and C varied from 14.4 to 72.5 percent.

Mean peak-sediment concentrations were measured at ten C stations during pioneering. Concentrations were 2256 mg/l, adding 1.56 pounds of sediment. Upstream, concentrations were usually less than 5 mg/l. When eight permanent culverts were installed, the sediment measured at C stations ranged from 0.22 to 603.75 pounds, and averaged 82.96 pounds. These measurements were strongly influenced by channel scour in some cases, and lack of sediment transport in others. Peak sediment concentrations ranged from 5.3 to 39,243 mg/l at C stations for ten permanent culvert installations, with an average of 5924.8 mg/l.

The sedimentation consequences of pioneering activities
at selected stream crossings in the Horse Creek watershed

| Stream crossing | Installation start time | Installation start date | Monitoring [1/] finish time | Monitoring [1/] finish date | Station A sediment lb | Station A discharge $ft^3$ sec | Station B sediment lb | Station B discharge $ft^3$ sec | Station C sediment lb | Station C discharge $ft^3$ sec | Mouth sediment lb | Mouth discharge $ft^3$ $sec^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18-1 [4/] | 1300 | 7/17/78 | 1955 | 7/17/78 | 0.06 | 0.02 | | | 1.72 | 0.04 | | |
| 18-2 | 1400 | 7/17/78 | 1955 | 7/17/78 | 0.42 | 0.02 | 3.20 | 0.04 | 25.13 | 0.06 | 12.13 | 0.92 |
| 18-3 | 1400 | 7/17/78 | 1955 | 7/17/78 | 0.01 | 0.01 | 2.04 | 0.01 | | | (9.19) [2/] | |
| 16-1 | 0800 | 7/11/78 | 0900 | 7/12/78 | 0.01 | 0.004 | 85.48 | 0.06 | 12.32 | 0.07 | | |
| 16-2 | 0800 | 7/11/78 | 0900 | 7/12/78 | 0.88 | 0.06 | | | | | 2.58 | 0.17 |
| 16-2 [5/] | 0810 | 7/18/78 | 1040 | 7/18/78 | 3.28 | 0.06 | | | | | (4.63) [2/] | |
| 15-1 | 1715 | 6/14/79 | 1425 | 6/15/79 | 0.36 | 0.01 | | | 1.44 | 0.01 | | |
| 15-2 | 1615 | 6/25/79 | 0945 | 6/26/79 | 0.10 | 0.004 | | | 0.06 | 0.006 | | |
| 14-1 | 0900 | 6/27/79 | 0800 | 6/28/79 | 0.67 | 0.04 | | | 213.26 | 0.06 | | |
| 14-2 | 0800 | 6/29/79 | 1500 | 6/29/79 | 0.03 | 0.04 | | | 41.51 | 0.04 | | |
| 14-3 | 0800 | 6/29/79 | 1500 | 6/29/79 | 0.05 | 0.02 | | | | | | |
| 14-4 | 1310 | 7/02/79 | 1600 | 7/02/79 | 0.02 | 0.006 | | | 0.003 | 0.004 | | |
| 12-1 | 1225 | 7/09/79 | 1700 | 7/10/79 | 0.45 | 0.04 | 12.56 | 0.04 | 5.32 | 0.09 | | |
| 12-2 | 1225 | 7/09/79 | 1700 | 7/10/79 | 0.32 | 0.03 | 2.81 | 0.03 | | | 11.20 | 0.21 |
| 12-3 | 1500 | 7/11/79 | 1300 | 7/13/79 | 1.51 | 0.02 | 154.71 | 0.02 | 112.20 | 0.03 | (3.19) [2/] | |
| 8-1 [3/] | 0910 | 7/24/78 | 0640 | 7/25/78 | 33.85 | 0.03 | | | 7.65 | 0.03 | | |
| 8-2 | 0820 | 8/08/78 | 1200 | 8/08/78 | 0.02 | 0.02 | | | 0.02 | 0.02 | | |
| 8-3 | 0820 | 8/08/78 | 1200 | 8/08/78 | | | | | | | | |

[1/] Monitoring duration at the “A,” “B” and “C” stations. The duration of monitoring at the mouths was considerably longer.
[2/] Values in parenthesis are predicted amounts of sediment for undisturbed conditions.
[3/] Monitoring the effects of pioneering in a seep area above the “A” station.
[4/] Effects of slash clearing.
[5/] Effects of culvert installation on Road 443.3 above the “A” station.

*King, 1981*

## 15.16 Bridge and Culvert Installation

In 1965, 8.47 miles of road in the Deep Creek drainage were rehabilitated. Ephemeral drainages were re-opened by digging channels across the road, fill was removed from draws and culverts, and dips constructed every 100 feet. Perennial grasses were seeded along the roadway. For decomposed granitic land types, using a dragline and D7 and D8 tractor for was recommended in future rehabilitation efforts using the same techniques. However, even with careful management, it seemed impossible to prevent accelerated sedimentation, and impossible to restore the natural hydraulic function once altered by road cuts.
*Jensen and Finn, 1966*

## 15.21 Maintenance of Roads

A study was performed to estimate cutslope erosion dealing with exposed tree roots. Increased erosion on cutslopes was found to be due primarily to road maintenance. “Removal of slough material at the base of the road cut during maintenance operation interferes with the natural slope-forming process, removes a favorable site for vegetation growth, and rejuvenates slope erosion processes.”
*Megahan, Seyedbagheri and Dodson, 1983*

## 15.22 Road Surface Treatment to Prevent Loss of Material

Chloride can exhibit toxicity towards plants and animals because the chloride ion stays in solution. A literature review has concluded that using calcium and magnesium is not without some environmental effects. These effects are usually found in the Northeast, where high concentrations of salts are used on a regular basis for wintertime deicing and summertime dust abatement. However, "for the purposed that the agency uses these compounds, little environmental effects are anticipated."
*Heffner, 1996*

In this study, three different surfacing materials were tested with simulated rainfall on six road sections. The test sites were blocked off, measuring 50- to 100-feet long by about 17 feet wide, with slopes ranging from 5 to 14 percent. Runoff was not measured. The cut-slopes were covered in plastic. Runoff was routed around the test sections in metal troughs to a modified cut-throat flume, where discharge was measured and sediment samples were collected. The rainfall simulation equipment was a large sprinkling infiltro-meter that uniformly applied rainfall over the plots at a rate of 2 inches/hour for 25 to 40 minutes.

The following data was collected from each plot:

1. Bulk-density in 0.1-foot increments to 0.3 feet below the road surface;
2. Quantity of loose soil on the roadway surface in pounds/foot$^2$;
3. Gravimetric soil moisture by depth determined by consistency before and immediately after simulated rainfall; and
4. Particle size distribution for each density, loose surface soil and suspended sediment sample.

Rillmeter measurements were taken before each simulated rainfall and again 24 hours after. Spaced 10 feet apart, samples were taken across the full width of the roadway.

Data showed "sediment yield is directly correlated with the amount of loose soil on the road surface and inversely correlated with the $D_{50}$, the mean size of the loose surface material." For bituminous surfacing and native material with dust oil, the hydrograph quickly climbs and then levels off to a near constant flow rate until the rainfall stops. Sediment yield on these protected surfaces is low. Sediment yielded from native material alone is 3.1 times greater than native material with dust oil, and 9.8 times greater than bituminous surfacing.
*Burroughs and others, 1984*

Another study took place in Silver Creek and Nez Perce. In Silver Creek, three surfaces – native granitic soil, native soil with dust oil, and native soil with bituminous dust oil – were tested on six road sections. Test plots were isolated from the adjacent roadway, and measured 5.2 meters wide x 15.25 or 30.5 meters long. Road slopes ranged from 5.3 to 10.3 percent. Runoff was not measured – the cut-slopes were covered with plastic, and runoff routed through a metal trough into a modified cutthroat flume set at 5 percent slope *(Skogerboe and others, 1973)*, to measure discharge and collect sediment samples. The sediment yielded from native material alone averaged 54.5 kg/100 m$^2$, 3.2 times greater than native material with dust oil, and 28.7 times greater than bituminous dust oil.

On the Nez Perce, two sections of a road at an 8 percent slope were re-contoured. The road was widened, in-sloped and graded. The cut-slope was shaped to a 1:1 back-slope, rolled and the upper section graveled. Two plots were established, one un-surfaced, and the other surfaced with a 10-centimeter layer of crushed gneissic rock. Each plot was 30.5 meters. Barriers and collection gutters were set up around the plots to separate road surface runoff from ditch runoff, which was measured in two flumes with flow-meters. Artificial rain was applied to each plot 14 times. Initial sediment yields were high. After several rainfalls, sediment declined rapidly because the fine particles were removed. After the eighth and ninth rainfalls, total sediment yielded from the road surface, ditch and cut-slope measured 881.3 kg. The cut-slope and ditch produced 773.1 kg, and the native-surface road produced 108.4 kg. Compared to the protected area, the unprotected cut-slope and ditch produced 6.3 times more sediment per 100 $m^2$ of tributary area than the native-surface road.
*Burroughs, Watts and Haber, 1985*

I n 1984, Swift completed a study of sediment yield from treated and untreated road segments. Bare travel-ways, and graveled travel-ways with light use, were measured before and after timber harvest for sediment yield in tons/acre/inch of precipitation. Results showed that on an un-surfaced travel-way, sedimentation increased by a factor of 1.90. By applying a 6-inch layer of 1½-inch minus crushed rock, sediment was reduced by 70 percent over five months.
*Burroughs and King, 1988*

## 18.05 Stabilization of Fire Suppression Related Watershed Damage

As previously shown *(Hibbert, 1967)*, as forest cover is reduced, water yield increases. With a 10 percent change in forest cover in conifer forests, a 40-millimeter change in annual water yield can be expected. Forest cover changes of less than 20 percent do not show changes in water yield detectible through streamflow measurements.
*Bosch and Hewlett, 1982*

## Bulk Density and Soil Compaction Summary

When a Clark 666 rubber-tired skidder made one or two passes, this did not result in substantial changes in bulk density. After four to 32 passes, bulk density was changed significantly. The rate of increase was from one to four passes. After four passes, bulk density remained fairly constant.

Comparing treatment years to one year after treatment, there was no considerable difference. The one-to-four-pass treatments showed differences between years. Bulk density increased with the one-to-four-pass treatment between years, and decreased with the four-pass treatment. “Four passes may be a threshold value beyond which rapid recovery does not occur.”

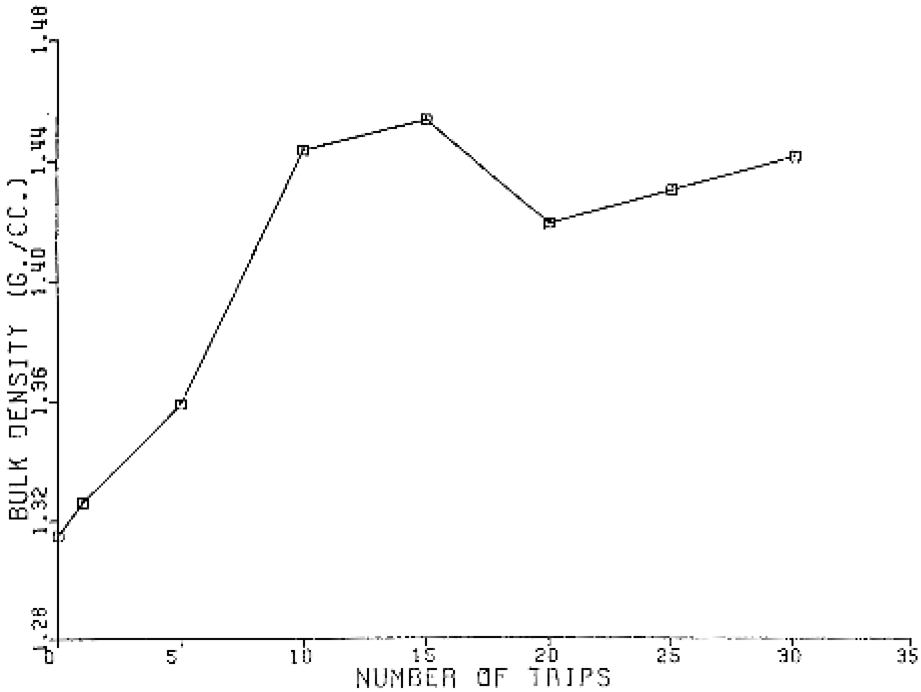
The one-pass treatment was the only one that changed the pore-size distribution index. Treatments with more than four passes seemed to show a redistribution of flow channels. This redistribution may alter plant growth and infiltration processes by reducing macropores.
*Lenhard, 1978*

Site impacts were evaluated for a study on removing thinning residue. The study tested a Case DH4 tractor that had been converted into a rubber-tired mini-skidder. Bulk density showed significant increases on skid trails (averaging from 5 to 7 percent of total stand area) for three out of four stands. A soil profile showed bulk density was limited to the upper 6 inches. "Average bulk density values for the upper 6 inches of soil on skid trails ranged from 1.11 to 1.43 in the lower half of the critical range." Reduced site productivity based on depth, aerial extent and degree of compaction showed minimal damage. From 70 to 80 percent of the total area was "undisturbed" or 'litter disturbed but still in place. "
*Rummer, 1982*

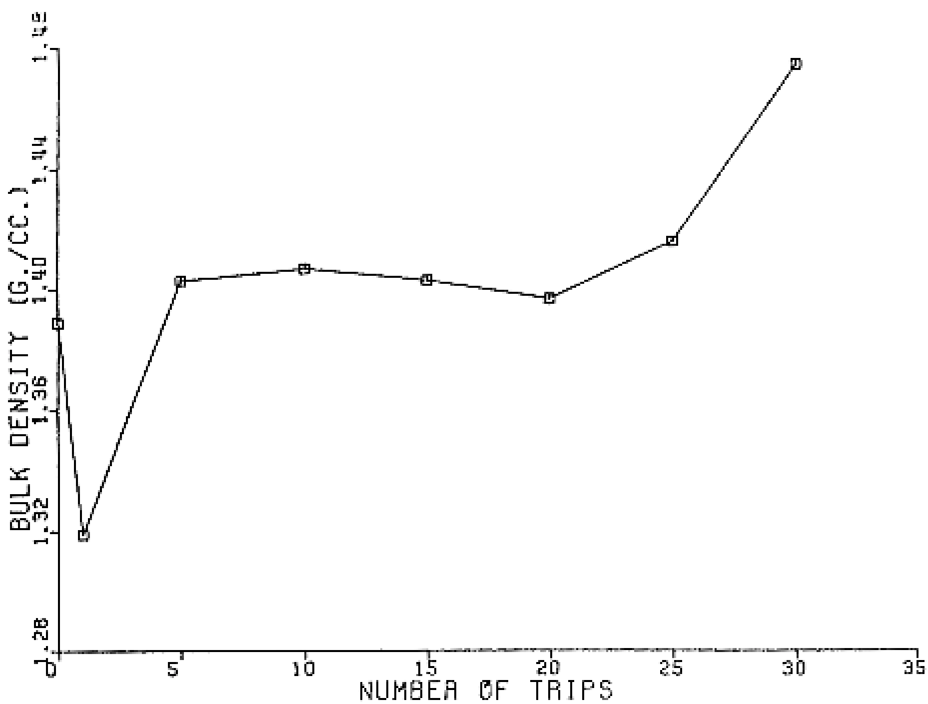
Skid trails were evaluated for soil bulk density on undisturbed areas and nearby ground-skidded partial-cut areas. Sites were sampled at depths of 5.1, 15.2 and 30.5 centimeters, with the interval since logging ranging from 0 to 25 years. Some sites were granitic and others volcanic. For both soil types, compaction was high and persistent. The granitic soils measured at 5.1 centimeters on the three oldest sites were the only samples where recovery had taken place.

For both soil types, the difference between undisturbed areas and skid trails proved highly significant for all other depths and intervals. The relationship between the difference in bulk density of skid trails v.s. undisturbed areas, and the time interval, was significant toward a trend in recovery. Recovery at 5.1 centimeters was much faster than all other depths and intervals. The volcanic soils showed a greater difference in bulk density between undisturbed areas and skid trails, than the granitic soils. However, even though recovery rates for both soil types did not prove greatly different, the volcanic soils had a higher initial compaction rate, nearly 2 times greater than the granitic soils.
*Froelich, Miles and Robbins, 1985*

A Case Davis Fleethoe 30 tractor was converted to a rubber-tired mini-skidder for skidding small diameter trees. Mineral soil was exposed on 13 percent of the area. In the top 2 inches of the soil, bulk density increased significantly, but not at depths of 4 to 6 inches, or 8 to 10 inches. The reason is most likely the dry soil conditions at the time of skidding. On a controlled unit with higher moisture content, the top 6 inches were compacted.
*Leverick, 1980*



Relationship of bulk density as a function of number of trips – soil depth 4 to 6 inches



Relationship of bulk density as a function of number of trips – soil depth 8 to 10 inches